

Remediation of colloid-facilitated contaminant transport in saturated porous media treated by nanoparticles

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Abstract Facilitation of contaminant transport in porous media due to the effect of indigenous colloidal fine materials has been widely observed in laboratory and field studies. It has been explained by the increase in the apparent solubility of low soluble contaminants as a result of their adsorption on the surface of fine particles. Attachment of colloidal fine particles onto the rock surface could be a promising remedy for this challenge. In this experimental study, the effect of five types of metal oxide nanoparticles, γ -Al₂O₃, ZnO, CuO, MgO, and SiO₂, on suspension transport was investigated. In several core flooding tests, different nanofluids were used to saturate the synthetic porous media. Subsequently, after sufficient soaking time, the suspension was injected into the treated porous media. Analysis of the effluent samples' concentration by Turbidimeter apparatus demonstrated that the presence of nanoparticles on the rock surface resulted in a significant reduction in fine concentrations in the effluent samples compared with non-treated media; ZnO and γ -Al₂O₃ demonstrated the best scenarios among the tests performed in this study. In order to characterize the surface properties of the treated porous media, the zeta potential of the surface was measured. Results showed that the treated

porous media acts as a strong adsorbent of fine particles, which are the main carrier of contaminants in porous media. These findings were quantitatively confirmed by calculation of the total energy of interaction between the fine particles and rock surface using the Derjaguin–Landau–Verwey–Overbeek theory.

Keywords Fine particles migration · Groundwater · Nanotechnology · Porous media · Subsurface colloids · Zeta potential alteration

Introduction

Groundwater contamination due to the spread of various chemical compounds, such as heavy metals, poisonous materials, and agricultural and industrial wastes, has been widely reported in the literature (Esmaeili Bidhendi et al. 2010; Lee and Jones 1993; Nouri et al. 2008; Simunek et al. 2006). The major mechanisms controlling the transport of contaminants may differ in the vadose and saturated zones (Sen and Khilar 2006). Until two decades ago, it was believed that contaminant transport in saturated porous media only occurred due to the motion of fluids existing in the subterranean reservoirs. It is now believed that part of the soil solid phase could play an important role in the transport of some contaminants. Colloid-facilitated transport of contaminants in saturated porous media has been suggested as an alternate mechanism to justify the unexpected appearance of low solubility contaminants far from their source (Grolimund et al. 1996; Grolimund and Borkovec 2005; Honeyman 1999; Kersting et al. 1999; Malkovsky and Pek 2008; McCarthy and Zachara 1989; Sen et al. 2002a, b). It has been explained by the increase in apparent solubility of low soluble contaminants due to their

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sorption on the surface of colloidal fine materials, which can act as a carrier of contaminants into the porous media (Honeyman 1999; Marseguerra et al. 2001; McCarthy and Zachara 1989; Richards et al. 2007). Generalized two and three-phase groundwater systems are compared in Fig. 1. Figure 1a depicts a two-phase system in which low soluble contaminants are distributed between an aqueous phase and immobile aquifer solids called the macroparticles. The third phase in Fig. 1b is colloidal fine particles or microparticles. Sorption of contaminants on the surface of the fine particles increases their apparent solubility and facilitates their motion into the porous media (Fig. 1b). Colloid-facilitated transport of contaminants is a dominant mechanism for transport of contaminants whose concentration is relatively low (Kretzschmar et al. 1999; McCarthy and McKay 2004; Sen et al. 2002a, b).

The abundance of contaminant metal elements and their mobility in porous media are functions of their sorption characteristics at the solid/liquid interface, which in turn depends on environmental properties, such as salinity, pH, suspended particles concentration, water velocity, temperature, and bedrock mineralogy (Kretzschmar et al. 1999; Sen 2001; Sen et al. 2002a, b; Wang et al. 2011; Xie et al. 2013; Yin et al. 2010). A variety of contaminants exist in porous media, but cationic forms of metals (e.g., Cs^+ , Cu^{2+} , Ni^{2+} , etc.) are the most frequently reported contaminants influenced by colloid-associated transport (Bradl 2004; Kersting et al. 1999; Sen et al. 2002a, b). Comprehensive experimental studies have been reported to investigate the role of colloidal fine particles on contaminant transport in porous media (Table 1). Roy and Dzombak (1996) reported significant enhancement of contaminant

transport by colloids. They conducted a systematic experimental study on Ni^{2+} contaminant transport through a sand-packed column containing indigenous mobilized colloidal particles. They observed that in the absence of colloids, outlet Ni^{2+} concentrations approached inlet concentrations after about 15 pore volumes; however, in the presence of colloids, it was reached only after 3 pore volumes. Kletzke et al. (2002) conducted some column experiments to investigate the effect of colloidal particles on the mobility of Pb^{2+} . According to their results, colloidal Pb^{2+} is much more mobile than dissolved Pb^{2+} . Therefore, according to the reported results, the motion of suspended particles and subsequent colloid-facilitated contaminant transport could provide an additional pathway for the transport of inorganic contaminants (Morales 2011; Simunek et al. 2006; Sun et al. 2010).

Some features of nanoparticles (NPs), such as their size, high specific surface area, adsorption characteristics, and heat conductivity, make them very interesting in a variety of engineering applications (Huang et al. 2008; Pourafshary et al. 2009; Rahbar et al. 2010; Rodriguez et al. 2009; Zhang et al. 2010). Recently, the remedial effect of nanoparticles on fine particles fixation in petroleum reservoirs has been reported. Fine particles detachment from the rock surface takes place as a result of repulsive forces existing between the particles and the rock surface. Therefore, fine particles migration in porous media can be prevented by the strengthening of the attractive forces with respect to the repulsive ones. There are indications in the literature to investigate the effect of nanoparticles on preventing in situ fine particles from being released and migrating within the porous media (Ahmadi et al. 2011; Habibi et al. 2011;

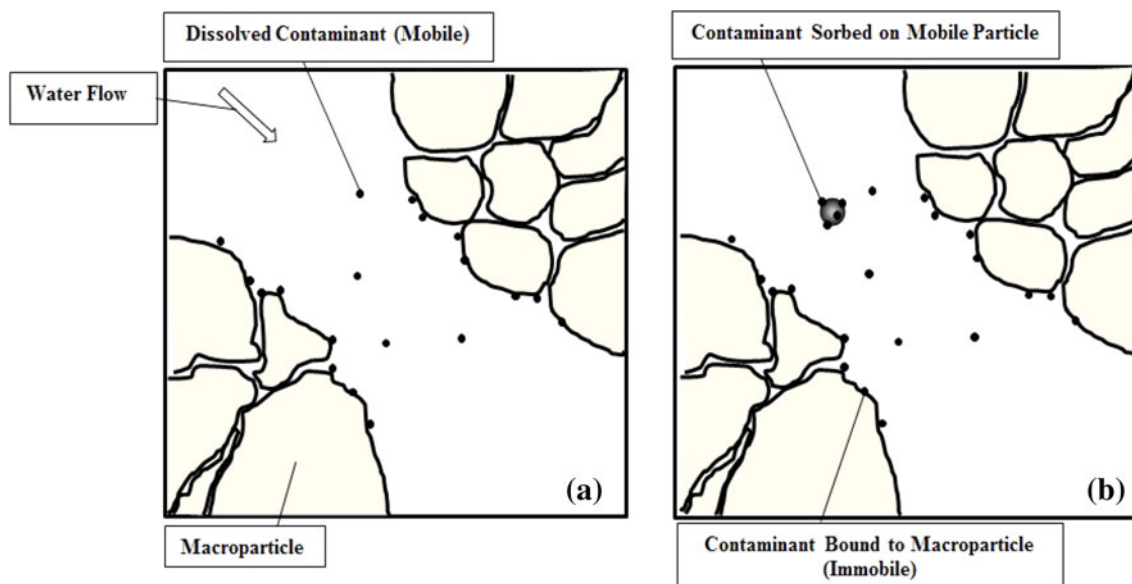


Fig. 1 Schematic view of groundwater systems: **a** two-phase; **b** three-phase



Table 1 Laboratory studies reported on colloid-facilitated contaminant transport in saturated porous media

Contaminants	Colloids	Porous media	References
Co ²⁺ , Sr ²⁺ , Cs ⁺	Clay minerals from porous media; neutron-activated for colloid tracing	Course sand (90 %) and clay or zeolite (10 %)	Torok et al. (1990)
Cu ²⁺ , Pb ²⁺ , Ni ²⁺ , Cr ²⁺	Clay and organic matter	Calcareous loam soil	Amrhein et al. (1993)
Phenanthrene, pyrene	Polystyrene latex, 76, 301 nm	Glass, 0.1, 0.2 mm, quartz sand ≈ 0.12 mm	Sojitra et al. 1995
Cs ⁺	Montmorillonite	Quartz sand	Faure et al. (1996)
Ni ²⁺	Natural colloids from Lincoln sand, 250 mg L ⁻¹	Ottawa sand	Roy and Dzombak (1996)
Cs ⁺	Silica, 100 nm, 200 mg L ⁻¹	Glass beads, 150–210 μm	Noell et al. (1998)
Cs ⁺ , I ⁻	Clay colloids (montmorillonite), 360 nm	Sand column 10 cm	Saiers (2002)

Huang et al. 2010; Ogolo et al. 2012). This effect was introduced by Huang et al. (2008) who used nanocrystals in proppant packs to fix the fine particles. Habibi et al. (2011) reported the remedial effect of MgO nanoparticles to fix the indigenous fine particles. They utilized distilled water injected into the porous media containing in situ fine particles. The presence of nanoparticles resulted in the reinforcement of attractive forces and in turn, the fixation of indigenous fine particles (Ahmadi et al. 2011; Habibi et al. 2011). In this study, the ability of different types of metal oxide nanoparticles, γ -Al₂O₃, ZnO, CuO, MgO, and SiO₂, to adsorb the already released fine particles was investigated. In several core flooding tests, a suspension containing natural fine particles was injected into the treated porous media, and the fine particles' concentration of effluent samples was analyzed. This research attempts to investigate the potential role of treated porous media as an adsorbent of suspended fines, which are the main carrier of contaminants in porous media. This research has been carried out in the Institute of Petroleum Engineering (IPE), University of Tehran (Tehran; Iran), between March and October 2012.

Materials and methods

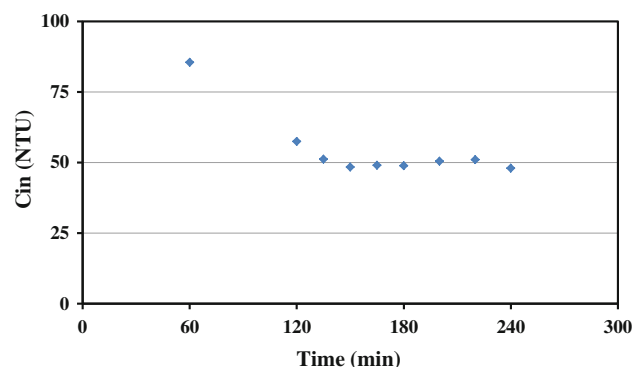
In several core flooding tests, the treated cores were flooded by the suspension. The suspension, including natural fines, cationic surfactant, and distilled water was prepared by magnetic stirrer. Because it is critical to have a suspension of constant concentration at the inlet during the tests, some preliminary tests were performed to achieve a stable suspension. In these tests, the fine particles' concentration of samples at different times was analyzed using a Turbidimeter apparatus (Hach 2100 Q) (Fig. 2). As can be inferred from Fig. 2, following 2 h settlement time, one can deduce that the suspension has a constant concentration. Therefore, after sufficient settling time, the stable

suspension was separated from the precipitation accumulating at the bottom of the container and was utilized for the flooding tests. This procedure is repeated for all the tests in order to verify an accurate influent concentration.

In the preliminary test, the average concentration of fine particles existing in the suspension was 50.56 nephelometric turbidity unit (NTU) (Fig. 2), which is the average of eight samples taken after 2–4 h settlement time.

A quantitative analysis of the utilized natural fine particles based on the X-ray fluorescence (XRF) method is presented in supplementary data file (Table S1). It should be noted that the mean grain size of the fine particles is between 1 and 10 microns.

In order to mimic underground reservoirs, spherical glass beads with an average diameter of 420–595 microns (30–40 U.S. mesh) were utilized as the porous media. The glass beads were packed into a sleeve of 11.5 cm length and 3.8 cm diameter. A prepared core was fitted into the core holder, and 700 psia overburden pressure was applied to its surroundings. In order to saturate the porous media, the packed bed was vacuumed for 2 h. Then, before each flooding test, the porous media was soaked for 24 h with nanofluid for each test and with distilled water for the reference test. The experimental setup is shown in Fig. 3.

**Fig. 2** Concentration of suspension in the preliminary test

During the flooding tests, the suspension containing fine particles was injected into the treated porous media and effluent samples at different pore volumes were collected and their fine particles concentration analyzed using a Turbidimeter apparatus.

Nanosized gamma alumina ($\gamma\text{-Al}_2\text{O}_3$), copper oxide (CuO), silica (SiO_2), magnesium oxide (MgO), and zinc oxide (ZnO) nanoparticles were purchased from U.S. Research Nanomaterials Company, and their characteristics are shown in Table 2.

Nanoparticles were uniformly dispersed in distilled water using an ultrasonic probe. The sizes of the nanoparticles in solution and the zeta potentials of the glass beads in the presence of nanoparticles were measured by the dynamic light scattering (DLS) method using a Zeta-sizer Nano series (Malvern Instrument Inc., London, UK, ZEN 3600).

Suspended nanoparticles existing in the nanofluid tend to agglomerate in the solution and form larger particles. In order to compare this characteristic of the utilized nanoparticles, the size of these aggregates was measured by the DLS method (Table 2). According to the results presented in Table 2, the size of gamma alumina nanoparticle

aggregates in solution is 113 nm, which is an indication of its good dispersion characteristic.

Results and discussion

Theory

The total energy of interactions existing between a fine particle and the pore surface consists of several contributors. These forces that include the electric double layer repulsion (EDLR), London–van der Waals attraction (LVA), Born repulsion, acid–base (AB) interaction, and hydrodynamic forces are quantified by Khilar and Fogler (1998). Calculation of these forces versus the distance of separation between a fine particle and the pore surface can determine whether the particles adhere to the surface or release and migrate in the porous media. The combination of EDLR, LVA, and Born repulsion is known as the Derjaguin–Landau–Verwey–Overbeek (DLVO) potentials (Bedrikovetsky et al. 2011; Derjaguin and Landau 1941; Khilar and Fogler 1998; Verwey and Overbeek 1948). The Born repulsion is a short-range potential that can be

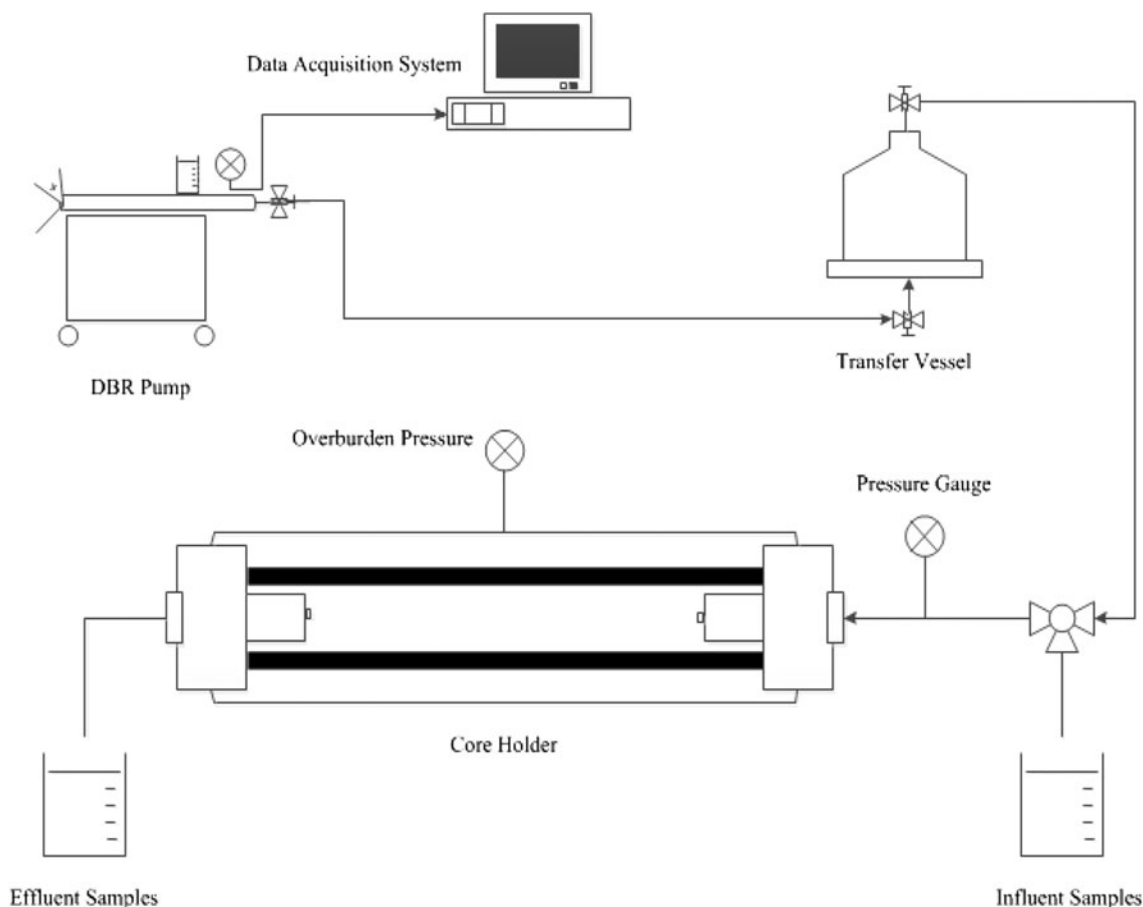


Fig. 3 Schematic view of experimental setup

Table 2 Characteristics of nanoparticles

Nanoparticles	Morphology	Specific surface area (m ² g ⁻¹)	Size according to manufacturer (nm)	Size according to DLS (nm)
γ-Al ₂ O ₃	Spherical	90–160	10–20	113
CuO	Nearly spherical	≈ 20	40	879
MgO	Tetragonal	>160	63	2,830
SiO ₂	Spherical	>600	48	587
ZnO	Nearly spherical	20–60	10–30	920

neglected compared with the other potentials, such as EDLR and LVA for distances of separation greater than 1 nm (Khilar and Fogler 1998). Because distilled water was used in all the tests in this study, the acid–base (AB) interaction is neglected. Therefore, the major forces controlling the interactions between the particles and pore surface, which should be determined in this study, are EDLR, LVA, and the hydrodynamic forces.

Electric double layer repulsion (EDLR)

Reduction in ionic strength of the permeating solution results in the expansion, and overlap of electric double layers formed at the pore surface and around the fine particle. Such an overlap of electric double layers of like-charge surfaces increases the EDLR energy, which causes detachment of fines from the surface. The EDLR energy of interaction is obtained by first solving the Poisson–Boltzmann equation with appropriate boundary conditions, in order to determine the potential profile from infinite to a small distance of separation. Hence, Eq. 1 is obtained for EDLR energy of interaction and for sphere–plate geometry of fine-pore surface system and constant potential boundary condition (Khilar and Fogler 1998).

$$V_{DLR} = \left(\frac{\epsilon_0 D_e a_p}{4} \right) \left[2 \psi_{01} \psi_{02} \ln \frac{1 + \exp(-\kappa h)}{1 - \exp(-\kappa h)} + (\psi_{01}^2 + \psi_{02}^2) \ln(1 - \exp(-2\kappa h)) \right] \tag{1}$$

Here, ϵ_0 is the electric constant (permittivity of free space), D_e is the dielectric constant, a_p is the fine particle radius, h is the distance of separation between a fine particle and the pore surface, ψ_{01} and ψ_{02} are the surface potentials of particles and collectors-grains, respectively (Bedrikovetsky et al. 2011; Khilar and Fogler 1998). The surface potentials can be replaced by the measured values of the zeta potentials. The inverse Debye length k is solely a function of the properties of the solution and not of any property of the surface, such as its charge or potential. The

dielectric constant for water D_e is 78.0, and the permittivity of free space (vacuum) ϵ_0 is equal to $8.854 \times 10^{-12} \text{ C}^{-2} \text{ J}^{-1} \text{ m}^{-1}$ (Bedrikovetsky et al. 2011; Israelachvili 2011; Khilar and Fogler 1998). The inverse Debye length k is equal to $(9.6 \times 10^{-9})^{-1} \text{ m}^{-1}$ for an aqueous solution (Khilar and Fogler 1998). The particle radius a_p is equal to 1,070 nm, which is obtained from DLS analysis of the suspension.

London–van der Waals attraction (LVA)

The London–van der Waals energy of interaction is a long-range attractive potential, which acts over distances as large as 10 nm. The LVA energy of interaction for the sphere–plate geometry is given as Eq. 2 (Khilar and Fogler 1998).

$$V_{LVA} = - \frac{A_{132}}{6} \left[\frac{2(1+H)}{H(2+H)} + \ln \left(\frac{H}{2+H} \right) \right] \tag{2}$$

where

$$H = h/a_p \tag{3}$$

Here, A_{132} is the Hamaker constant between a pore surface and a fine particle separated by an aqueous medium. The Hamaker constant is equal to $6 \times 10^{-21} \text{ J}$ in calculations relating to the release of fine particles (Khilar and Fogler 1998).

Born repulsion

Electron clouds overlap when the particles approach the point of contact, which results in a short-range potential known as the Born repulsive potential. This potential has a dominant effect when the distance of separation is smaller than 1 nm and it can be neglected for larger distances compared with the EDLR and LVA potentials. It is given in Eq. 4 for the sphere–plate system (Khilar and Fogler 1998).

$$V_{BR} = \frac{A_{132}}{7,560} \left(\frac{\sigma}{a_p} \right)^6 \left[\frac{8+H}{(2+H)^7} + \frac{6-H}{H^7} \right] \tag{4}$$

Here, σ is the atomic collision diameter in Lennard-Jones potential and is equal to 0.5 nm (Khilar and Fogler 1998).

Hydrodynamic forces

In addition to the colloidal forces, fine particles are subjected to the hydrodynamic forces of the flowing fluid. Hydrodynamic repulsion energy depends on the flow velocity and fine particles’ size. In porous media, the fluid flow is usually laminar and does not provide enough lift

force to detach the particles from the surface (Khilar and Fogler 1998; O'Neill 1968). The repulsive potential due to hydrodynamic forces for laminar flow in porous media is presented in Eq. 5 (Khilar and Fogler 1998).

$$V_{HR} = \left(\frac{2\pi\rho}{3} \right) \frac{a_p^5 v^2 h}{R^3} \quad (5)$$

Here, R is the radius of the pores and is equal to 32×10^{-6} m (Khilar and Fogler 1998) and ρ is the density of the liquid, which is equal to $1,000 \text{ kg m}^{-3}$ for the suspension used in the flooding tests. In all of the performed tests, the flow rate of suspension injection was held constant at 4 mL min^{-1} . In this work, there are no initial indigenous fine particles situated on the pore walls; however, attachment of suspended particles onto the pore walls can take place during suspension injection. Therefore, a lifting force may exist due to the hydrodynamic forces exerted on the already adsorbed fine particles. It must be mentioned that due to the small size of the fine particles and the low fluid velocity in all the tests in this study, the hydrodynamic energy is not comparable with the EDLR and LVA potentials.

Total energy of interactions

An equation for the total energy of interaction is obtained by algebraically adding all the contributions. Negative and positive signs represent the attractive and repulsive energy, respectively. The total interaction energy of the system consisting of a fine particle (sphere) and a pore surface (plate) is given in Eq. 6.

$$V_T = V_{DLR} + V_{LVA} + V_{BR} + V_{HR} + V_{AB} \quad (6)$$

As mentioned previously, due to the use of distilled water, the acid–base (AB) interaction is neglected in this study. The dimensionless form of the total energy of interaction is shown in Eq. 7 (Khilar and Fogler 1998).

$$V_{T, \text{Dimensionless}} = \frac{V_T}{K_B \times T} \quad (7)$$

Here, K_B is the Boltzmann constant and is equal to $1.38 \times 10^{-23} \text{ JK}^{-1}$ (Khilar and Fogler 1998) and T is temperature, which equal 297 K for the conditions of the tests.

Core flooding tests results

As mentioned in the previous section, in the reference test, the vacuumed porous media was saturated with distilled water, whereas in the other tests, it was saturated with different types of nanofluids. The specifications of the performed tests are presented in Table 3.

During core flooding tests, effluent samples were collected at different times and their fine particles'

concentration was measured by Turbidimeter apparatus. The results of the different tests are compared in Fig. 4. All the values are dimensionless with respect to the pertinent influent particle concentration.

The results presented in Fig. 4 indicate that the presence of nanoparticles on the surface of grains in the synthetic porous media results in a critical reduction in fine particles' concentration in the effluent samples compared with the non-treated media. As shown in Fig. 4, the test performed in the presence of ZnO nanoparticle has the lowest values for effluent fine particles' concentration. In addition, γ - Al_2O_3 and MgO nanoparticles show considerable tendencies to collect the fine particles from the flowing suspension.

In order to check out the repeatability of the experiments, each flooding test has been repeated for three times and the pertinent results are presented in the supplementary data file (Fig. S1–5). The results reported in Fig. 4 are the average of particles concentration breakthrough profiles obtained in different tests performed at the completely same conditions. It is noteworthy to mention that the experiments in which the medium treated by ZnO and γ - Al_2O_3 nanoparticles have been repeated for five times to check out their distinguished remedial effects on suspension transport in the medium (Fig. S4 and Fig. S5). As inferred from Fig. S1–5, the flooding tests are acceptably repeatable and the nanoparticles-treated media tend to adsorb the suspended particles in different sets of experiments.

The turbidity of effluent samples obtained at pore volumes of 1, 3, 5, and 7 of the reference test and the test in the presence of ZnO nanoparticles are compared in Fig. 5.

Turbidity is an indicator of fine particles' presence in the effluent samples. As inferred from the Fig. 5, the turbidity of samples obtained from the reference test is much greater than that obtained from the test in the presence of ZnO nanoparticles. The comparison of samples obtained at different pore volumes shows that the effect of nanoparticle treatment is durable and that fine particles are adsorbed by the treated porous media even after continuous injection of seven pore volumes.

Calculation of total energy of interaction

The zeta potential is a criterion indicating the electric potential in the interfacial double layer (DL), surface charges, and colloid characteristics. In order to investigate the effect of nanoparticles treatment on the surface properties of glass beads, the zeta potential of the glass beads for different cases was measured by the DLS method (Table 4).

According to the zeta potential analysis presented in Table 4, the presence of nanoparticles on the surface of

Table 3 Specifications of the experiments

Property	Reference test	Test with γ -Al ₂ O ₃ NP	Test with CuO NP	Test with MgO NP	Test with SiO ₂ NP	Test with ZnO NP
Pore volume (cm ³)	47	50	51	51	50	52
Porosity (%)	33.85	38.14	38.89	38.89	38.14	39.66
Applied overburden pressure (psia)	700	700	700	700	700	700
Influent suspension concentration (NTU)	48.85	59.20	50.50	64.05	68.22	46.80
Flow rate (mL min ⁻¹)	4	4	4	4	4	4
NP concentration (wt%)	–	0.03	0.03	0.03	0.03	0.03

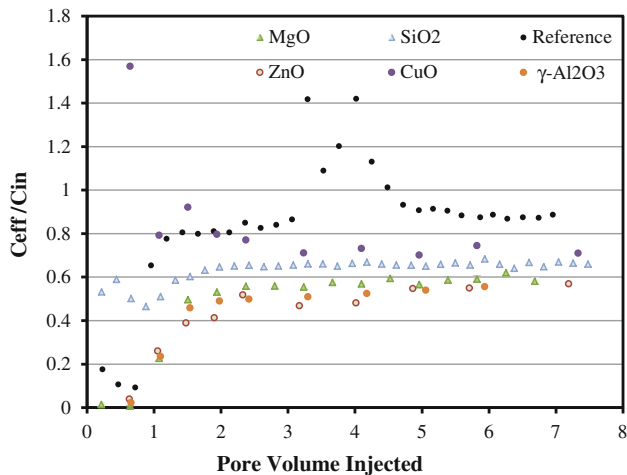


Fig. 4 Dimensionless form of effluent fine particles concentration

glass beads results in a zeta potential alteration, which disturbs the force balance between the particles and the rock surface. The total energy of interaction existing between the fine particles and rock surface was calculated for different scenarios, and the results are presented in Fig. 6. As mentioned previously, the Born repulsion term is negligible for distances of separation greater than 1 nm (Khilar and Fogler 1998). The dimensionless form of the total energy of interaction was calculated using Eq. 7, and the results are presented in Fig. 6b.

As inferred from the results presented in Fig. 6, at distances of separation smaller than 1 nm, the total energy is strongly repulsive. At these distances, the effect of the Born repulsion energy is dominant and causes detachment of fine particles from the rock surface. At larger distances, the Born repulsion term is negligible compared with the EDLR and LVA potentials. At distances greater than 2 nm, because of the EDLR effect, the total energy is repulsive for the reference case compared with the nanoparticle treated cases; therefore, fine particles detachment from the rock surface occurs. For the nanoparticle treated scenarios, due to the zeta potential alteration of the surface, the total energy of interaction is negative (attractive) and as a result, fine particles attach to the rock surface. The more positive

Table 4 Zeta potential for different cases

Case	Zeta potential of glass beads (mV)
Test with γ -Al ₂ O ₃	+0.82
Test with CuO	–7.45
Test with MgO	0.11
Test with SiO ₂	–13.6
Test with ZnO	+1.57
Reference Test	–44

the zeta potential of the surface, the less electric double layer repulsion energy, and thus, there is greater attachment of fine particles onto the rock surface. The differences among the different cases result from the different capability of nanoparticles on zeta potential alteration of rock surface. The presence of ZnO nanoparticles on the surface of glass beads results in alteration of the zeta potential from –44 to +1.57 mV, which makes the total energy of interaction more attractive. These results justify the results of the core flooding tests (Fig. 4), in which effluent fine particles’ concentrations have the lowest values for the case treated by ZnO nanoparticles.

According to Fig. 6, the total energy of interaction for the case treated by SiO₂ nanoparticles is less attractive compared with the case treated by CuO nanoparticles. This is in disagreement with the results of the core flooding tests presented in Fig. 4. According to Fig. 4, fine particles’ concentration of effluent samples obtained from the SiO₂ nanoparticles-treated case is of lesser value compared with the case treated by CuO nanoparticles. This is because of the stronger adsorption ability of the SiO₂ nanoparticles due to the higher specific surface area compared with CuO nanoparticles. Specific surface area is a controlling parameter in adsorption phenomena. The specific surface area of SiO₂ nanoparticles is more than 600 m² g⁻¹; therefore, the presence of SiO₂ nanoparticles on the surface of the glass beads provides more collector sites for the fine particles to be attached on to the surface. Furthermore, according to the results presented in Table 2, SiO₂ nanoparticles were dispersed uniformly in solution and their

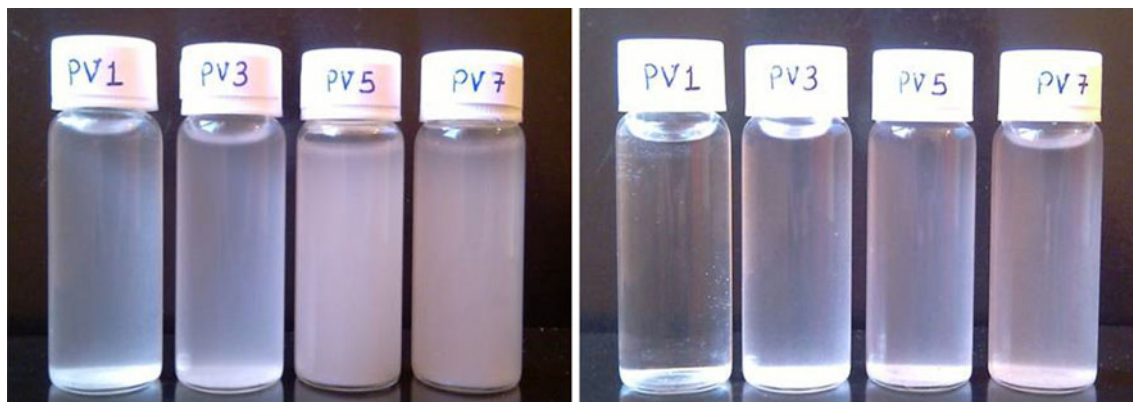
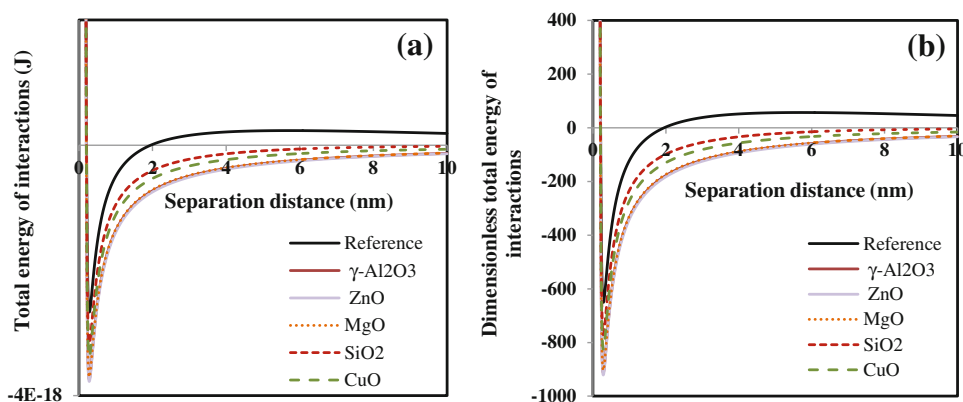


Fig. 5 Effluent samples obtained at different pore volumes for the reference test (*left*) and for the test in the presence of ZnO nanoparticles (*right*)

Fig. 6 **a** Total energy of interactions versus separation distance; **b** dimensionless form of total energy of interactions versus distance of separation



aggregates are 587 nm in size. Therefore, due to the very high specific surface area of SiO₂ nanoparticles and the good dispersion characteristics, glass beads treated by SiO₂ nanoparticles are better adsorbents of fine particles compared with the glass beads treated by CuO nanoparticles.

Conclusion

Nanoparticle treatment to prevent the spread of fine particles, which are the main carriers of contaminants in porous media, was investigated. Five types of metal oxide nanoparticles were selected to investigate their ability to adsorb the suspended fine particles. ZnO and γ -Al₂O₃ nanoparticles were found to be the best remedial agents among the utilized nanoparticles. The fine particles' concentration of effluent samples, obtained from core flooding tests, was around 50 % of the influent suspension concentration for the case treated by ZnO nanoparticles. The presence of nanoparticles on the rock surface alters the surface characteristics and the zeta potential of the porous media, which are the main parameters affecting the fine particles' fate. Due to the deposition of ZnO nanoparticles on the surface of glass beads, the zeta potential of the surface was

changed from -44 to $+1.57$ mV. The calculated total energy of interaction existing between the fine particles and the surface of the porous media confirmed the experimental results. For the porous media treated by nanoparticles, total energy of interaction was more attractive compared with the non-treated case.

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